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# Soil moisture–temperature relationships: results from two field experiments

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## Abstract:

This paper analyses data from two field experiments in Chickasha, Oklahoma, and Tifton, Georgia, carried out in July 1999 and June 2000 respectively. The observations on soil moisture at two depths, *viz.* 0–2·5 and 0–5·0 cm, surface temperature, and temperatures at 1, 5 and 10 cm depths are analysed. The relationship between the soil moisture and the temperature variability in time is examined as a function of vegetation type and location. Results from these experiments show that, during drydown, surface temperature shows an increase that corresponds to a decrease in the soil moisture. Linear models for prediction of soil moisture (at both depths) using surface temperature observations are examined. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS soil moisture; surface temperature; field experiments

## INTRODUCTION

The estimation of soil moisture and temperature is critical to the understanding of land surface–atmosphere interactions. Soil moisture is an important variable of the water and energy cycle, as it helps determine the proportion of rainfall partitioned into runoff, surface storage, and infiltration components, as well as partitioning of incoming solar and longwave radiation into outgoing longwave radiation, latent, sensible, and ground heat flux (through the dependence of albedo on moisture content). Along with soil moisture, surface temperature is a key variable in determining the land surface heat and water balance. The surface temperature determines the fluxes of outgoing longwave, sensible, and ground heat. The magnitude of these fluxes determines the latent heat flux (i.e. evapotranspiration by the energy balance principle). Therefore, changes in surface temperature affect soil moisture and *vice versa*.

The primary link between the energy and water balance equations is the evapotranspiration (evaporation and transpiration and latent heat) term in both equations. Understanding the relationship between soil moisture and surface temperature will enable us to estimate and predict evapotranspiration, as well as other heat fluxes, which can lead to better climate predictions.

Previous field studies (Idso *et al*., 1975b; Reginato *et al*., 1976) have focused on the relationship between volumetric soil moisture (averaged over a day) and the diurnal amplitude of the surface temperature measurements (2:00 pm minus 2:00 am). These studies are based on the thermal inertia concept, i.e. a wetter soil will exhibit smaller surface temperature amplitude due to the thermal inertia of the water in the soil. Other studies (Idso *et al*., 1974, 1975a) have provided relationships between albedo and volumetric soil moisture. In both cases, a connection has been made between the water and the energy balance variables facilitating the estimation of the volumetric soil moisture by remote (or *in situ*) observation of the energy/radiation-connected variable.

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Observations and estimation of surface temperature and soil moisture are difficult, as both are spatially variable (as a function of soil type, land cover, and land use) and temporally variable (on diurnal, seasonal and annual time scales). In order to understand the relationship between soil moisture and surface temperature, field studies must be conducted to obtain accurate and reliable (simultaneous in time and coincident in space) soil moisture and surface temperature observations. Field measurements of surface temperature have been used for validation of satellite-retrieved surface temperatures (Lakshmi *et al*., 1998; Prince *et al*., 1998; Lakshmi and Susskind, 2000).

Our work is motivated by the following problem: in practice, microwave sensors that detect and retrieve soil moisture have footprints an order of magnitude larger in size than those of infrared/thermal sensors detecting surface temperatures. An example is the 6·6 GHz channel of the Advanced Microwave Scanning Radiometer (AMSR; Wilson *et al*., 2001), which has a 50 km footprint. The Advanced Very High Resolution Radiometer (AVHRR; (Kidwell, 1995; Campbell, 1996) that is used to estimate infrared temperature has a much smaller footprint (1 km). Therefore, it may be possible to use surface temperatures from satellite sensors to disaggregate (improving the spatial information) the microwave-retrieved soil moisture. The focus of this work is to explain possible connections between surface temperature and soil moisture in order to carry out such a task in the future.

In this paper we study the relationships between soil moisture and temperature at the surface and various depths. In addition, we study the temporal evolution of soil moisture and temperature, and the relationship between variables. These (above-mentioned relationships) differ with land-cover types. We also study the use of *in situ* surface temperature using simple linear regression models to predict soil moisture.

## STUDY REGIONS AND FIELD EXPERIMENTS

### Study sites

*Little Washita watershed, OK.* The site of the Southern Great Plains 1999 Experiment (SGP99) was the Little Washita (LW) watershed, which is located in southwest Oklahoma near Chickasha (35°27′N, 097°56′W), in the Southern Great Plains Region of the USA (Figure 1). The experiment was carried out in the watershed between 8 July and 20 July 1999 (both days inclusive). The watershed is 605 km$^2$ in area with a moderately rolling topography that has a relief of about 200 m (Allen and Naney, 1991). Individual fields were approximately 800 m × 800 m. The study area experienced varying amounts of rainfall (37·0 mm in the western part of the watershed to about 9·6 mm in the eastern part) on 10 July 1999, and a subsequent drydown period was observed during the rest of the study. The watershed includes both coarse- and fine-textured soils (Jackson, 2001). There were five types of land cover studied in the experiment: rangeland, wheat, corn, alfalfa, and fallow; rangeland fields make up the majority of fields studied (Table I).

*Little River watershed, GA.* The Little River (LR) watershed is located in southern Georgia near Tifton (31°27′N, 083°30′W) in the coastal plains region of the USA (Figure 2). The study was carried out in the watershed between 5 June and 9 June 2000 (both days inclusive). The watershed is 334 km$^2$ in area and is characterized by broad flood plains with poorly defined stream channels and gently sloping uplands (http://sacs.cpes.peachnet.edu/sewrl). The study area experienced varying amounts of rainfall (48·0 mm in the central-western part of the watershed to about 2·0 mm in the northernmost part) on 5 June 2000, and a subsequent drydown was observed during the rest of the study period. Watershed soils are predominantly sandy loam (85%) in the upland areas and coarser closer to the streams. There were six types of land cover studied in this experiment: pasture, corn, forest, peanuts, cotton and grassland; no particular land cover dominated the area (Table II). The fields are 800 m × 800 m in size.

 

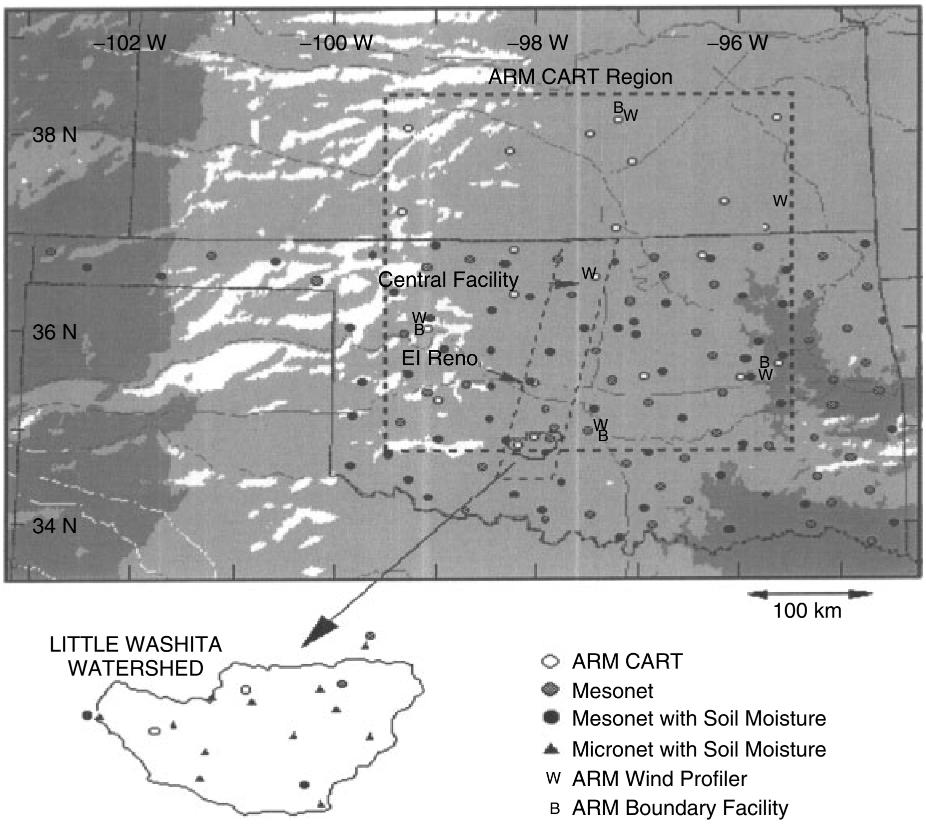


Figure 1. SGP99 study region and Little Washita watershed (source: http://hydrolab.arsusda.gov/sgp99/)

*In situ field observations*

In both the field studies, surface temperature was measured daily using Everest handheld infrared thermometers (IRTs). In both of these field experiments, groups of scientists from USDA, NASA, various universities and research organizations (including the authors of this paper) participated in the collection of the data. Soil temperature at depths of 1, 5 and 10 cm (soil temperature at 5 cm was not measured at the Little River watershed) were measured daily with Checktemp temperature probes. (Brand names are provided here and elsewhere in this paper for reference purposes only and by no means constitute an endorsement by the University of South Carolina or the US Department of Agriculture). Both, the temperature probes and the IRTs have an accuracy of $+/-0{\cdot}1\,^{\circ}C$. Each field has varying quantities of temperature observations due to weather (Little Washita watershed only), and availability and operation of the sampling apparatus (both watersheds). Almost none of the Little Washita fields had measurements for 10 July 1999, due to rainfall during the sampling time. The rainfall at the Little River watershed occurred after sampling had been completed on 5 June 2000; therefore, the routine temperature sampling was not disrupted during the week due to weather. During both studies, measurement of soil temperature at 10 cm depth was not possible when the soil was dry, as probes could not be driven to that depth (without breaking) to carry out measurements.

In both field studies, soil moisture was quantified using the gravimetric technique. Surface temperature and soil moisture sampling were intended to estimate the field (800 m $\times$ 800 m) average. In both field studies, a rectangular grid was set up on each field to obtain spatially distributed samples. In the case of SGP99, two types of sampling design were undertaken, *viz.* full and profile, which differed only in the amount of samples taken. In a full sampling field, soil moisture was sampled at 14 locations, whereas surface and soil temperature

 

Table I. Little Washita fields, the predominant land cover for that field, and the sampling protocol associated with that field. Profile fields have nine measurements (for soil moisture and temperature) rather than four (temperature) or 14 (soil moisture) measurements taken on a full field

| Field | Land cover | Sampling protocol |
|---|---|---|
| 02 | Range | Full |
| 03 | Range | Full |
| 04 | Range | Full |
| 05 | Range | Full |
| 06 | Range | Profile |
| 07 | Range | Profile |
| 08 | Wheat | Profile |
| 09 | Range | Profile |
| 12 | Range | Full |
| 13 | Range | Full |
| 14 | Range | Profile |
| 21 | Wheat | Full |
| 22 | Wheat | Full |
| 23 | Wheat | Full |
| 24 | Fallow | Full |
| 25 | Corn | Full |
| 26 | Corn | Full |
| 27 | Alfalfa | Full |

was sampled at only four of these 14 locations. These locations were arranged on a rectangular grid in a $2 \times 7$ formation with a 100 m separation between locations. In a profile sampling field, nine temperature and soil moisture samples were taken at random (unbiased) locations within each field. A profile field is an area of 50 m $\times$ 50 m around a weather station. The sampling carried out here was in a limited area with nine observations without any pre-specified grid pattern. However, unlike the full sampling field at SGP99, both soil moisture and temperature measurements in the Little River watershed were only made at four locations for any given field for soil moisture and temperature. The central issue in this mode of sampling is that there is temporal and spatial collocation of the soil moisture and soil temperature samples. In all analyses, the individual soil moisture and temperature values observed at several locations in each field have been averaged to obtain the mean value of the variable for the field. In this study, we use field-averaged quantities rather than individual observations.

It should be noted that, as far as possible, measurements were carried out at approximately the same time every day (around 9:00 am local time). This is critical specifically in the case of surface temperature (and, to decreasing degrees, the 1, 5 and 10 cm temperatures), due to the dependence on the time of day of measurement. The majority of the observations were recorded prior to 10:00 am. However, the exact time of observation has not been recorded, and this introduces an additional factor in our analysis. Therefore, our conclusions (for temperature) are dependent on the time of day of observations.

## *IN SITU* DATA COMPARISON

### *Little Washita, OK*

*General trends in temperature and soil moisture.* SGP99 provided an opportunity to observe soil moisture and surface temperature changes during a drydown period. In the beginning of the study (9 July 1999), the

 

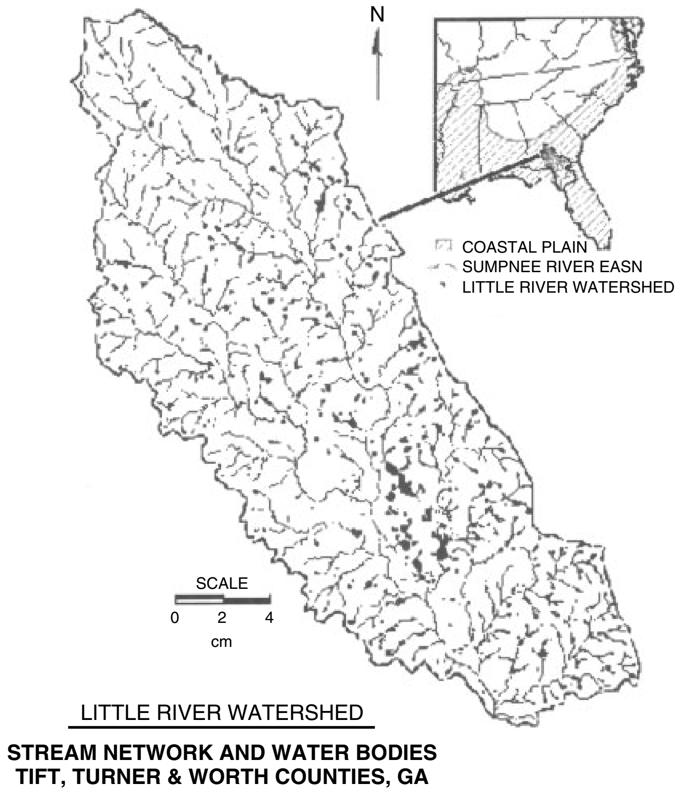


Figure 2. Little River watershed (source: http://www.cpes.peachnet.edu/sewrl)

soil surface was dry over most of the Little Washita watershed. On 10 July 1999, there were varying amounts of rainfall over the study region (37·0 mm in the western part of the watershed to about 9·6 mm in the eastern part), which saturated the surface (around 2–3 cm), providing a starting point of the drydown sequence. After 10 July 1999 (or the beginning of the drydown sequence), there is a gradual downward trend in soil moisture and an upward trend in temperature. The above-described patterns in temperature and soil moisture were observed to be independent of land-cover type.

The temporal variations in temperature averaged over four (full) or nine (profile) measurements, and soil moisture averaged over 14 (full) or nine (profile) measurements for the fields studied during the experiment are shown in Figure 3 (rangeland fields: LW02, 06, 12, 14), Figure 4 (wheat fields: LW08, 21, 22, 23), and Figure 5 (corn: LW25, 26, fallow: LW24; alfalfa fields: LW27).

Temperature measurements, at depths of 1, 5 and 10 cm, are all very close (within 4 °C of one another) and exhibit the same pattern in increases and decreases over time. The surface temperature had the largest magnitude (compared with other surface temperatures for all other times) before 10 July 1999 (e.g. LW02, LW12), and generally temperature decreases with an increase in depth (e.g. LW06, LW14) for the rangeland fields. For example, field LW12 (Figure 3), the surface temperature had an average value of 29·4 °C on 9 July 1999, while at a 1 cm depth the temperature was 27·6 °C and at 5 cm it was 27·3 °C. For the fields that did not have surface temperature measurements (wheat, fallow, alfalfa, and corn fields), we observed that the temperature values followed the same trend as seen with the rangeland fields; temperature values decrease with an increase in depth (e.g. LW21, LW24, LW26; Figures 4 and 5).

On the first day of sampling for field LW12 (Figure 3) after the rain event, surface temperature drops down to become the lowest temperature value (of all the temperatures) and temperature values increase with depth

 

Table II. Little River fields and the predominant land cover

| Field | Land cover |
|---|---|
| 01 | Corn |
| 02 | Pasture |
| 03 | Cotton |
| 04 | Forest |
| 05 | Cotton |
| 08 | Corn |
| 09 | Peanuts |
| 10 | Peanuts |
| 11 | Pasture |
| 13 | Peanuts |
| 15 | Peanuts |
| 16 | Cotton |
| 17 | Forest |
| 18 | Peanuts |
| 19 | Cotton |
| 20 | Forest |
| 21 | Pasture |
| 22 | Cotton |
| 23 | Grass |

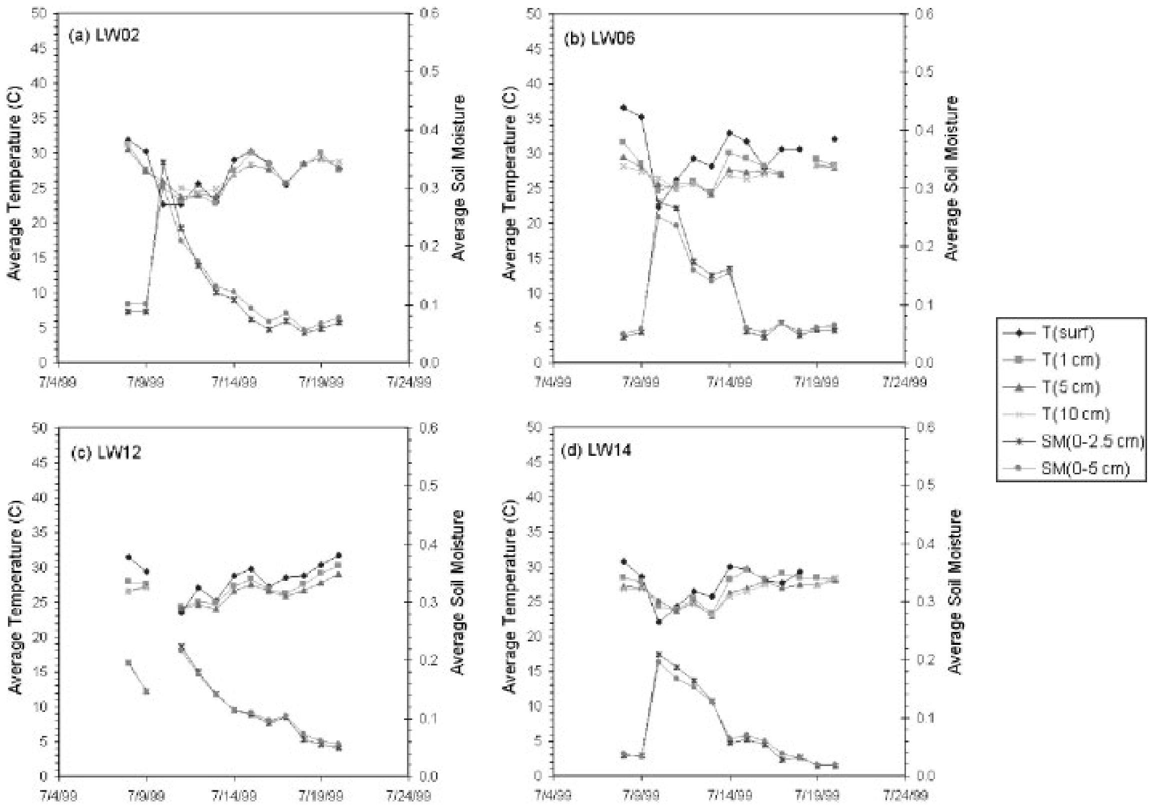


Figure 3. Variability of the average temperature (°C) and soil moisture trends over time for rangeland fields: (a) LW02; (b) LW06; (c) LW12; (d) LW14. Gaps represent missing data

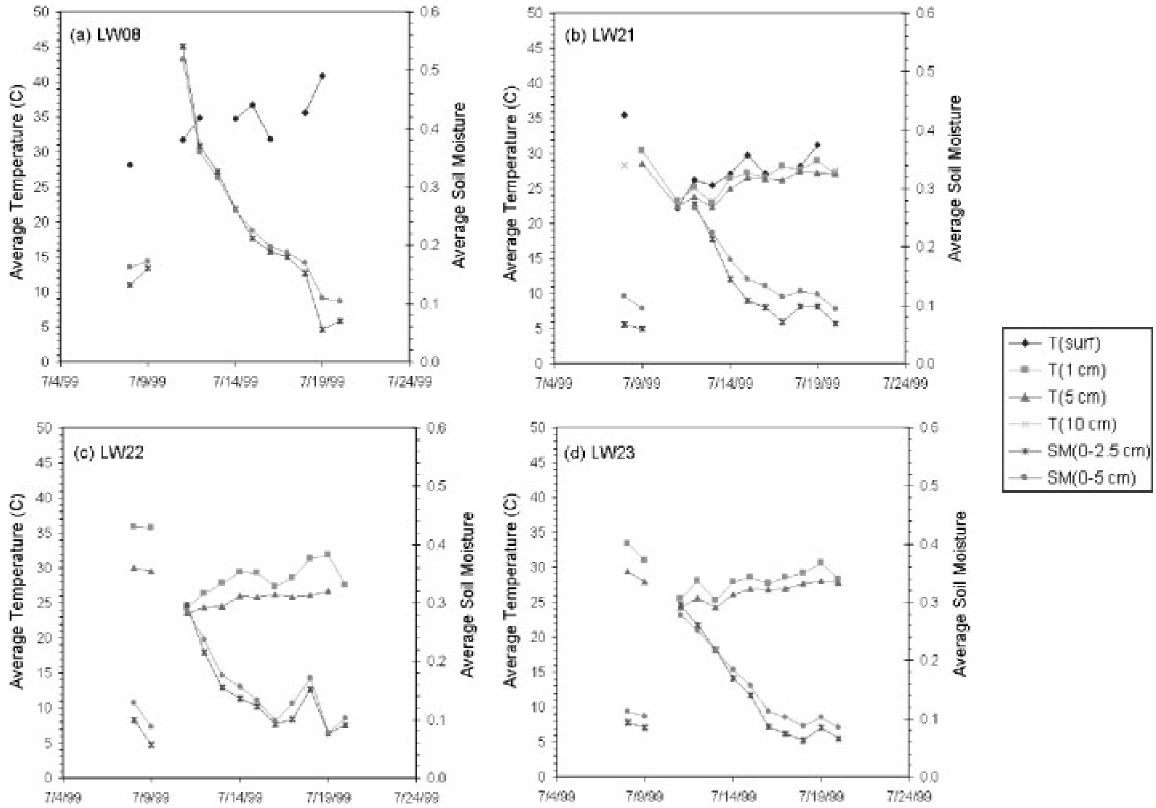


Figure 4. Variability of the average temperature (°C) and soil moisture trends over time for wheat fields: (a) LW08; (b) LW21; (c) LW22; (d) LW23. Gaps represent missing data

(23·5 °C at the surface, 24·3 °C at 1 cm, and 24·5 °C at 5 cm). However, it must be noted that the accuracy of the soil temperature probe is ±0·1 °C; therefore, these observations should be treated with caution. This reverse in trend is the result of the wet surface promoting evapotranspiration, and hence lowering of temperature and the cooling effect decreasing with depth. In all of the rangeland fields the surface temperature exhibited the largest change in values between the day prior to the rainfall event and the day after the rainfall event (9 July and 11 July 1999); field LW12 exhibited a change of 5·9 °C for surface temperature, a change of 3·3 °C for $T$(1 cm), and a change of 2·8 °C for $T$(5 cm).

In the fields where surface temperature was not collected, there was a consistency with the above fact, *viz*. the slopes of the temperature–time plots become shallower with an increase in depth. Field LW23 (wheat field) exhibited a change of 5·6 °C for $T$(1 cm) and a change of 3·6 °C for $T$(5 cm) between (both days inclusive) 9 July and 11 July 1999 (Figure 4). We observed that surface temperature had the highest value (at the end of the study period) with the exception of LW02 and LW14 (among surface temperature, 1, 5 and 10 cm).

Closer analysis of the soil moisture data showed that, prior to the rainfall event (and for a majority of the fields), the 0–5 cm depth had a higher volumetric soil moisture value than the 0–2·5 cm depth. The deeper soil layers will have more soil moisture than the top soil layers due to evaporation (drying) at the surface, which is then followed by the upward movement of moisture (exfiltration) from the deeper soil layers to the surface (for bare soils) and transpiration (for vegetation-covered soils). On 10 July 1999, the 0–2·5 cm depth had a larger increase in soil moisture than the 0–5 cm depth. This is due to the wetting action of the rainfall, which proceeds from the surface downwards. However, the amount of water that reaches the deeper soil

 

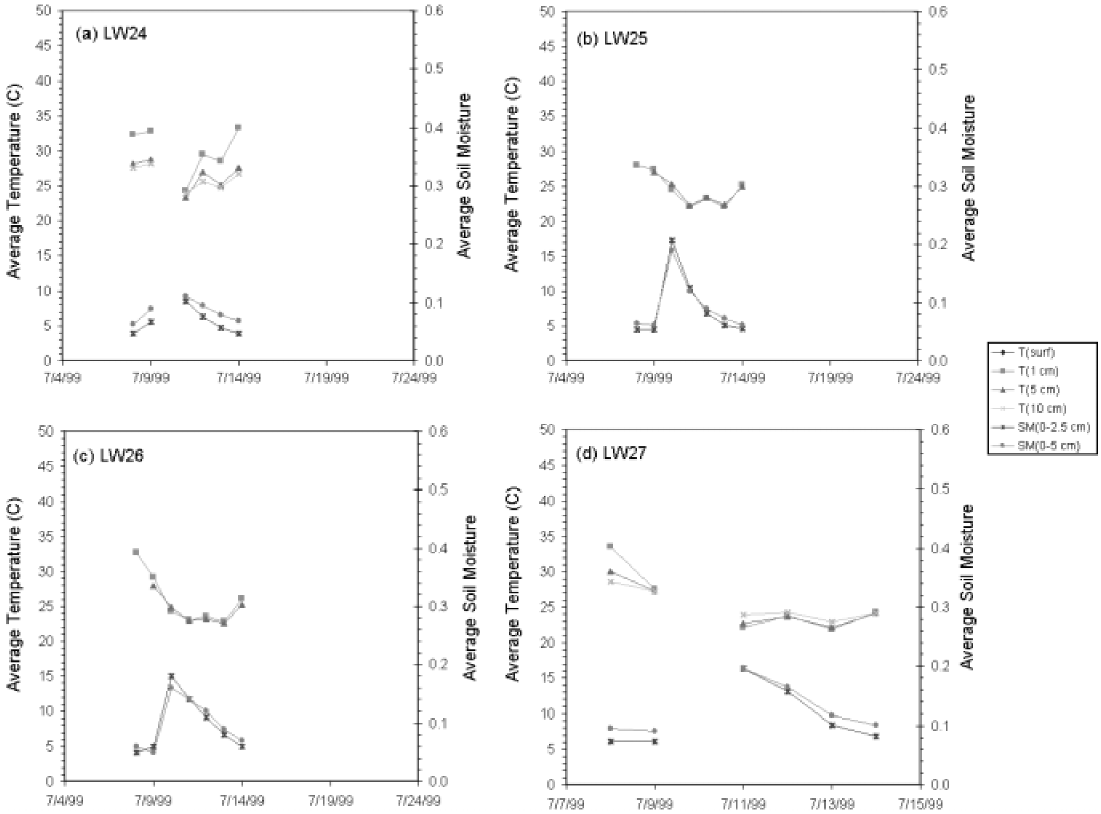


Figure 5. Variability of soil moisture and temperature for: (a) fallow fields, LW24; for corn fields, (b) LW25 and (c) LW26; (d) alfalfa fields, LW27. Gaps represent missing data

layers is less than what is seen at the surface, due to evaporation of the infiltrating water. When the drydown commences, we observe that the 0–2·5 cm depth loses moisture at a faster rate in the first few days after the rain event than the 0–5 cm depth (e.g. LW21, LW24, LW26; Figures 4 and 5); also, the 0–2·5 cm depth proceeds to have less moisture than the 0–5 cm depth over time (e.g. LW04, LW21, LW26; Figures 3–5).

LW08 (Figure 4) dries at a faster rate ($-0{\cdot}16$ day$^{-1/2}$, $-0{\cdot}14$ day$^{-1/2}$ for 0–2·5 cm and 0–5·0 cm volumetric soil moisture respectively) and warms up faster at the surface (1·125 °C day$^{-1}$) than LW21, which dries at ($-0{\cdot}093$ day$^{-1/2}$, $-0{\cdot}081$ day$^{-1/2}$) and warms at the surface at the rate of 0·822 °C day$^{-1}$. Even though less precipitation fell over LW08 (29 mm) than LW21 (39 mm), LW08 had a higher starting point (initial soil moisture for 0–2·5 cm around 0·17) than LW21 (around 0·06), thereby resulting in higher soil moisture after the precipitation event.

*Linear regression for temperature and soil moisture.* The goal of this study was to see if there were unique trends in the soil moisture–temperature relationship associated with specific land-cover types. Figure 6 (rangeland fields: LW02, 06, 12, 14) uses the same data that was studied in the previous section, but displays temporal trends for temperature and soil moisture data collected between 10 July and 20 July 1999 (both days inclusive; the drydown period). The horizontal axis in Figure 6 represents the transformed axis $t^{1/2}$, where $t$ is the number of days elapsed following the rain event (1 signifies first day of sampling after the rainfall). We have plotted the soil moisture versus $t^{1/2}$ and temperature versus time, as we carry out linear regressions between these two pairs of variables.

 

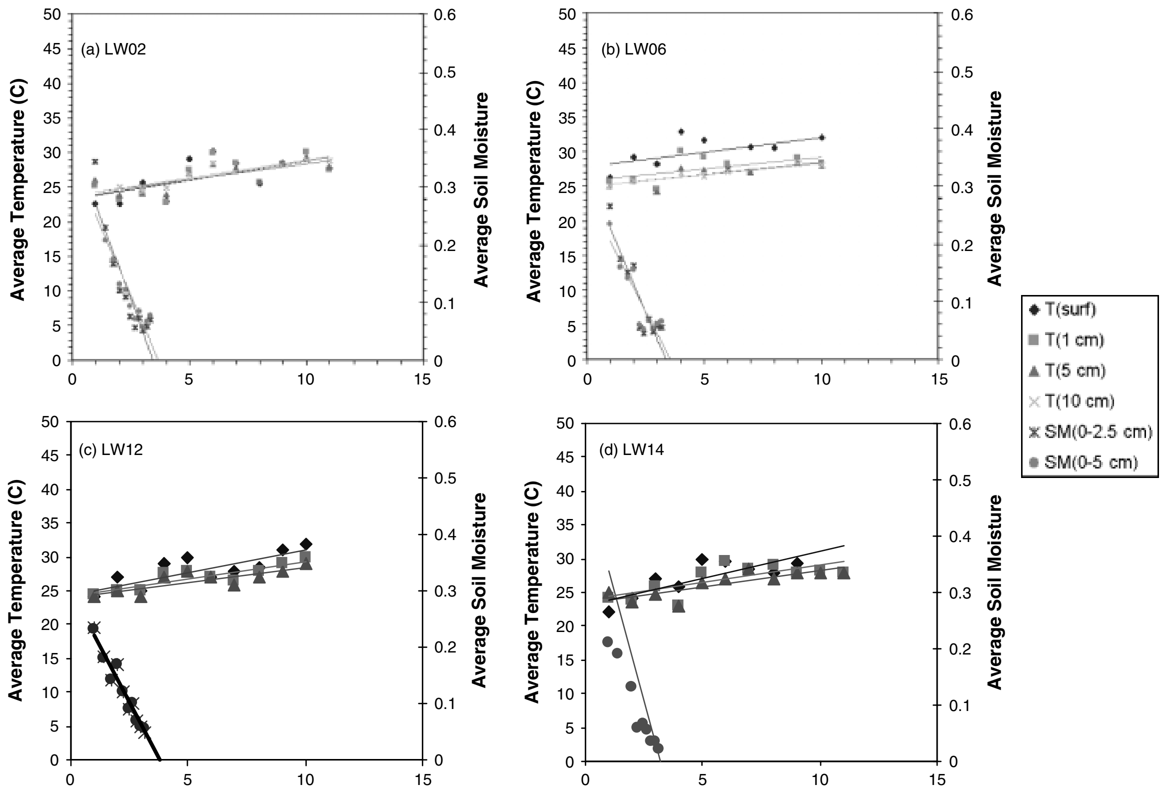


Figure 6. Average temperature (versus time; 12 July 1999 = 2·0) and soil moisture (versus time$^{1/2}$; 12 July 1999 = 1·4) trends using a linear regression fit during a drydown period for the rangeland fields (a) LW02, (b) LW06, (c) LW12 and (d) LW14. The *x*-axis is the number of days after the rainfall (10 July 1999, being day 0)

Table III shows the different magnitude trends (slopes) for different land-cover types. The numbers in the table associated with the rangeland fields are the most reliable, since we have maximum data acquired from ten separate fields, for this land-cover type. The means and standard deviations calculated in Table III do not include the data collected over LW05, as the data from this field have linear slope values that are greater than two standard deviations of the means when compared with the other fields included in the analysis. In general, the slope of the mean temperature and mean standard deviation decreased with soil depth. It is observed that a wheat field warms up (at the surface) at an average rate of $+0{\cdot}82\,^{\circ}\mathrm{C}\ \mathrm{day}^{-1}$, which is faster than a rangeland field, which on average warms up at a rate of $+0{\cdot}57\,^{\circ}\mathrm{C}\ \mathrm{day}^{-1}$. At a temperature depth of 1 cm, a fallow field warms up the fastest at an average rate of $+2{\cdot}6\,^{\circ}\mathrm{C}\ \mathrm{day}^{-1}$, followed by rangeland, alfalfa and wheat fields, which all have about the same warming rate of $+0{\cdot}45$ to $0{\cdot}47\,^{\circ}\mathrm{C}\ \mathrm{day}^{-1}$; a corn field warms up the slowest, at a rate of $+0{\cdot}26\,^{\circ}\mathrm{C}\ \mathrm{day}^{-1}$ after the rainfall event. The same rates apply for temperatures at a depth of 5 cm. The order of warming trend (from the largest to the smallest) proceeds as follows: fallow, wheat and rangeland, alfalfa, and corn (which were much drier throughout). Observations of soil moisture trends reveal that, for the 0–2·5 and 0–5 cm depth intervals, the rates are a function of land-cover type. Overall, the 0–2·5 cm depth soil moisture trend has a steeper slope than the 0–5 cm soil moisture trend. At both depths, alfalfa fields dry down at the fastest rate, on average at $-0{\cdot}12\ \mathrm{day}^{-1}$ (0–2·5 cm) and $-0{\cdot}10\ \mathrm{day}^{-1/2}$ (0–5 cm); the corn, the rangeland and the wheat, and the fallow fields drydown at progressively smaller rates.

The percentage variability in Table III is the standard deviation of measurements (temperature, soil moisture) divided by the mean, and is used to show the spatial variability in temperature and soil moisture over a sampling

 

Table III. Fields grouped by land cover showing rates of temperature (versus time) warming and soil moisture (versus time$^{1/2}$) drying during the drydown period of the study, 10 July to 20 July 1999. In the first column, the fields are grouped together by land cover and the mean, the standard deviation of the mean, and percentage variability, which pertains to the group of fields that are represented. A plus sign represents a positive slope and a negative sign represents a negative slope

| Field | Slopes (°C day$^{-1}$) temperature | | | Slopes (day$^{-1/2}$) soil moisture | |
|---|---|---|---|---|---|
| | Surface | 1 cm | 5 cm | 0–2·5 cm | 0–5 cm |
| Range mean | +0·567 | +0·451 | +0·414 | −0·101 | −0·088 |
| Standard deviation | 0·104 | 0·134 | 0·106 | 0·023 | 0·017 |
| Variability (%) | 6·17 | 5·25 | 3·63 | 38·16 | 33·41 |
| Wheat mean | +0·822 | +0·472 | +0·442 | −0·098 | −0·086 |
| Standard deviation | 0·000 | 0·077 | 0·118 | 0·018 | 0·010 |
| Variability (%) | 5·95 | 9·04 | 5·18 | 37·59 | 30·67 |
| Fallow mean | | +2·62 | +1·08 | −0·055 | −0·044 |
| Variability (%) | | 7·84 | 2·51% | 31·19 | 20·66 |
| Corn mean | | +0·262 | +0·043 | −0·111 | −0·088 |
| Standard deviation | | 0·129 | 0·021 | 0·018 | 0·020 |
| Variability (%) | | 3·20 | 1·92 | 25·81 | 27·56 |
| Alfalfa mean | | +0·458 | +0·243 | −0·120 | −0·100 |
| Variability (%) | | 3·71 | 2·34 | 24·99 | 21·14 |

field for each day. The spatial variability decreases with an increase in temperature depth for all land-cover types except wheat. Meteorological conditions affect the surface greater than soil at a 5 cm depth, thereby creating the greater spatial variability at the surface. The spatial variability in the soil moisture measurements was much larger than seen in the temperature measurements. The soil moisture variability is a function of the variability in vegetation and temperature, both of which control evapotranspiration. These results (decrease of spatial variability with depth) are complementary to those of Famiglietti *et al.* (1999), who showed that the spatial standard deviation of soil moisture increases during a drydown period.

A linear trend fit to the data is adequate for a small number of fields (provides high correlation specifically for soil moisture, less so for temperature). In general, the trend is non-linear specifically for temperatures. The soil moisture exhibits a (close to) linear trend compared with surface temperatures.

### *Little River, GA*

*General trends in temperature and soil moisture.* At the beginning of the study (5 June 2000) the soil was dry over most of the Little River watershed. On the afternoon of 5 June 2000, there were varying amounts of rainfall over the study region (48·0 mm in the central-western part of the watershed to about 2·0 mm in the northernmost part), which saturated the surface, providing a starting point of the drydown sequence. After 5 June 2000 (or the beginning of the drydown sequence), there is a gradual downward trend in soil moisture and a corresponding upward trend in temperature. Unlike the observations during the SGP99 experiment, the temperature measurements at all three depths did not exhibit an immediate drop in temperature after the rain event. Instead, most of the fields exhibited their lowest temperatures 2 days after the rain event, creating a very non-linear trend during the drydown period for temperature. The soil moisture peaked on the day after the rainfall (6 June 2000) for almost all of the fields (as observations on 5 June were carried out before the rainfall). These patterns in temperature and soil moisture were observed to be independent of land-cover type.

The temporal variations in temperature and soil moisture for LR02 (pasture), LR04 (forest), LR15 (peanuts), LR16 (cotton) and LR23 (grass) are shown in Figure 7. The overall trends in temperature and soil moisture were similar for all of the fields.

 

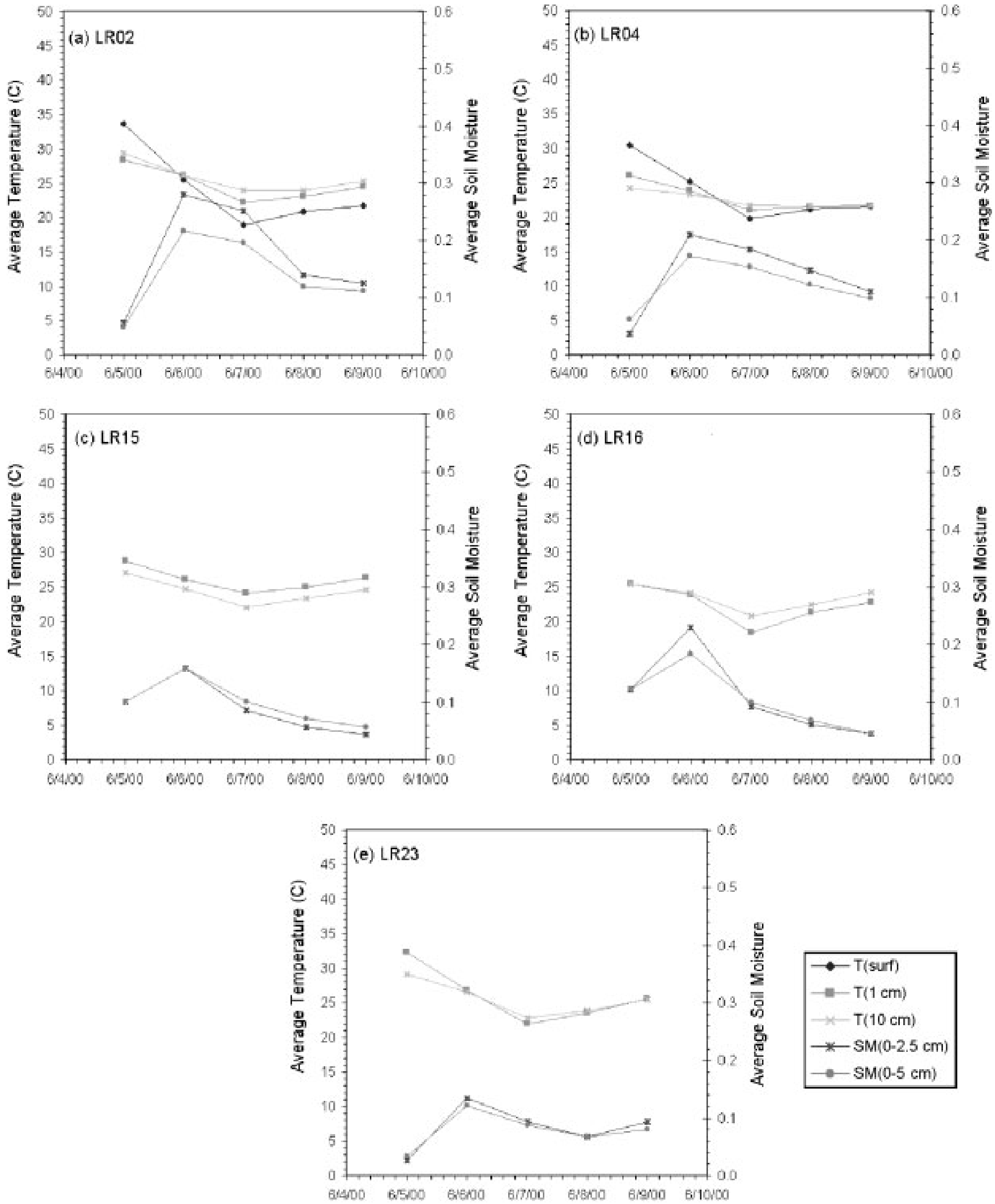


Figure 7. Average temperature (°C) and soil moisture trends over time for: (a) pasture, LR02; (b) forest, LR04; (c) peanut, LR15; (d) cotton, LR16; (e) grass, LR23

Temperature measurements at depths of 1 and 10 cm are very close, within 3 °C of one another, and exhibit the same pattern of increase and decrease over time. However, over the 5 day study, we observe that there is significant change in temperature at any of the depths. The surface temperature had the greatest value on 5 June 2000 (e.g. LR02, LR04), and temperature values for all of the fields are independent of land-cover type. In the case of field LR04 the surface temperature had an average value of 30·5 °C on 5 June 2000, while at a 1 cm depth the temperature was 26·0 °C and at 10 cm it was 24·2 °C. Field LR04 was the only field from this study that showed good contrast between temperatures at the three depths on 5 June 2000. A majority

 

(∼85%) of the other fields showed temperature values at 1 and 10 cm within 1–2 °C of each other. Thus, there is no contrast between temperatures at different depths, as was seen in the SGP99 experiment.

On the first day of sampling after the rain event (6 June 2000) the surface temperature drops, but, unlike in SGP99, the surface temperature does not become the lowest temperature value. There was no pattern observed, such as an increase in temperature with depth. Surface temperature drops to become the lowest temperature value distinctly in only three of the eight fields where it was measured, and the temperature values at 1 and 10 cm are close in value, within 2 °C. No pattern was observed that showed one being consistently greater than the other (between the 1 and 10 cm temperatures) or *vice versa*.

Surface temperature did not drop drastically in comparison with the other temperature measurements at the deeper soil layers after the precipitation event. We did not observe the expected temporal trend (surface temperature having the largest value by the end of the study, as seen during SGP99). However, this can be attributed to the shorter duration (5 days versus 10 days for SGP99) of this study. We also did not observe the dramatic cooling effect that rainfall had on the surface, nor an attenuation of this effect at deeper soil depths. We observed that the temperature takes 2 days to drop to its lowest value after the rainfall. This was evident in the non-linear shape of the temperature variability, with the minimum on 7 June 2000, seen in all of the fields. This could be due to the modulation of the water and heat budget by the vegetation effect on precipitation. The vegetation (initially after the precipitation) shields the soil from evaporation and the maximum evaporation occurs 2 days after the event. A major portion of vegetation in the Little River watershed is broad-leafed trees and shrubs—peanuts, cotton, forests (pecan)—and these have a considerable shadow effect on the soil surface.

Closer examination of the soil moisture observations showed that, prior to the rainfall event (for some of the fields), the 0–5 cm depth had a slightly higher volumetric soil moisture value than the 0–2·5 cm depth, unlike the SGP99 observations. Differences between the soil moisture at the depth intervals (0–2·5 and 0–5 cm) on 5 June 2000 were minor/negligible for a majority of the fields. This could be due to the fact that in some of the fields the soil was very dry and had no compaction, such as LR10, 11, and 13, making it hard and almost impossible to split the soil sample accurately into two distinct layers (0–2·5 and 2·5–5 cm). When this occurred, the same value was used for both the 0–2·5 cm depth and the 0–5 cm depth. However, the same general (temporal) patterns that were seen in SGP99 were seen in the Little River study with regard to soil moisture. On 6 June 2000, we observed that the 0–2·5 cm depth had a larger increase in soil moisture (from 5 June 2000) than the 0–5 cm depth. It is on this day that most of the fields had the largest difference in soil moisture between the two depth intervals. The only field that did not have a peak of soil moisture on 6 June 2000 was LR17, which was a forested site. When the drydown period begins, we observe that both depths lose moisture at about the same rate after the rain event (e.g. LR16 with the exception of 7 June). The trend observed at SGP99 during the drydown period was that the 0–2·5 cm depth proceeds to have less moisture than the 0–5 cm depth over time. This trend was observed in some of the Little River fields (e.g. LR02, 23), but not in the majority of the fields. We observed that there are more fields with either the 0–5 cm depth having more moisture or the two being about the same (within 0·01).

The soil moisture and temperature trends are affected by the vegetation and soil type, and the amount of rainfall received by that field. In comparing a peanut field in the south-central part of the watershed (LR13) with a peanut field that is 0·05° longitude west and 0·2° latitude north of LR13 (LR18), we noticed that the two fields had a different magnitudes of change the day before the rainfall and the day after. Field LR13, which received approximately 38·0 mm more rainfall than LR18, had an increase in soil moisture (0–5 cm) of 0·14 and a decrease in temperature at 1 cm (10 cm) of 4·7 °C (3·5 °C). Field LR18 exhibited an increase in soil moisture (0–5 cm) of 0·03 and a decrease in temperature at 1 cm (10 cm) of 2·8 °C (2·1 °C). This implies that the locational aspect, i.e. amount of precipitation received, plays an important role in the soil moisture drydown and temperature increase over time.

*Linear regression for temperature and soil moisture.* Figure 8 depicts the linear trend for the fields in Figure 5 (LR02 (pasture), LR04 (forest), LR15 (peanuts), LR16 (cotton) and LR23 (grass)) for temperature

 

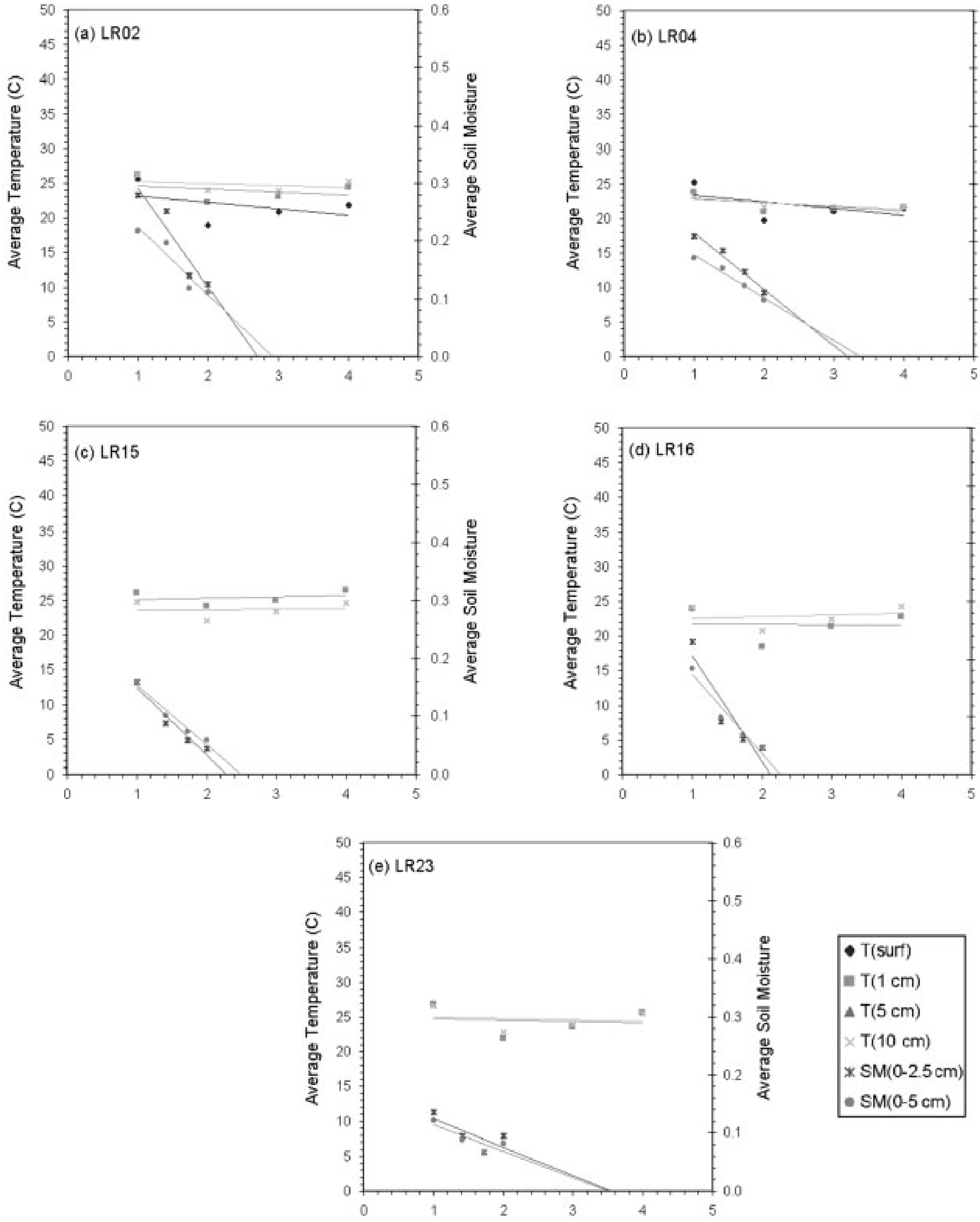


Figure 8. Average temperature (versus time; 7 June 2000 = 2·0) and soil moisture (versus time$^{1/2}$; 7 June 2000 = 1·4) trends using a linear regression fit during a drydown period for: (a) the alfalfa field, LR02; (b) forest, LR04; (c) peanuts, LR15; (d) cotton fields, LR16; (e) grass fields, LR23 (grass). The *x*-axis is the number of days after the rainfall (5 June 2000, being day 0)

and soil moisture data collected between (both days inclusive) 6 June and 9 June 2000, the drydown period. The *x*-axis in Figure 8 represents the number of days after the rain event (1 signifies first day of sampling after the rainfall), rather than the day the measurement was actually made (6 June 2000).

Table IV shows that different magnitude trends (slopes) are associated with different land-cover types. There is a wide variation of vegetation in the Little River watershed. The greater is the spread around the mean

Table IV. Fields grouped by land showing rates of temperature warming and soil moisture drying during a shorter drydown period, 7 June to 9 June 2000. In the first column, after the listing of fields grouped together by land cover is a row for the mean and a row for the standard deviation, A plus sign represents a positive slope and a negative sign represents a negative slope

| Field | Slopes (°C $day^{-1}$) temperature | | | Slopes ($day^{-1}$) soil moisture | |
|---|---|---|---|---|---|
| | Surface | 1 cm | 10 cm | 0–2·5 cm | 0–5 cm |
| Corn mean | +1·65 | +1·30 | +0·850 | −0·136 | −0·109 |
| Standard deviation | 0·00 | 0·566 | 0·420 | 0·033 | 0·007 |
| Pasture mean | +1·45 | +0·950 | +0·630 | −0·221 | −0·165 |
| Standard deviation | 0·00 | 0·350 | 0·325 | 0·135 | 0·098 |
| Cotton mean | +2·18 | +1·54 | +1·28 | −0·077 | −0·074 |
| Standard deviation | 1·52 | 0·708 | 0·853 | 0·020 | 0·013 |
| Forest mean | −0·200 | +0·050 | +0·400 | −0·063 | −0·046 |
| Standard deviation | 2·68 | 0·901 | 0·212 | 0·042 | 0·034 |
| Peanuts mean | +2·50 | +1·52 | +1·25 | −0·059 | −0·049 |
| Standard deviation | 0·00 | 0·476 | 0·173 | 0·016 | 0·015 |
| Grass mean | — | 1·85 | +1·35 | −0·003 | −0·011 |

(higher the standard deviation), the less is the confidence in the actual averages. An interesting observation to note about the five (LR02, 04, 15, 16, and 23) fields mentioned is that they all lie in the very northern part of the watershed, which did not receive much rainfall (on 5 June 2000), creating different hydrological trends compared with the fields that received significant amounts of rainfall.

In the case of the peanut fields, we observed that the surface temperature had the steepest (regressed) slope (1·99 °C $day^{-1}$) and slope decreases with depth in the soil (0·108 °C $day^{-1}$ at 1 cm, 0·042 °C $day^{-1}$ at 10 cm), which supports our observation that the surface will be affected by the rainfall the greatest and this effect will decrease at lower soil depths. Examination of the soil moisture trends revealed that, for the 0–2·5 and 0–5 cm depth intervals, the rates (slopes) vary for the different land-cover types. For both depths, a pasture field dries down the fastest, at a rate on average of −0·20 $day^{-1/2}$ (0–2·5 cm) and −0·16 $day^{-1/2}$ (0–5 cm); the corn, cotton, peanuts, and grass fields (in that order) drydown at progressively slower rates.

The temperature linear regressions $R^2$ are low on all of the fields, except for the surface ($R^2 = 0{\cdot}867$) and 1 cm ($R^2 = 0{\cdot}886$) temperature measurements for LR18 and the 1 cm layer ($R^2 = 0{\cdot}852$). On average, the correlation value for surface temperature was 0·294; for 1 cm of was 0·202, and for 10 cm it was 0·077. In general, the soil moisture linear regressions for both 0–2·5 cm and 0–5 cm, fit the measured *in situ* data very well (average $R^2 = 0{\cdot}885$), independent of land-cover type. The time transformation that was used for soil moisture resulted in slightly better individual field correlation values (increase in $R^2$ on average 0·02, maximum increase of 0·09) and no real improvement of standard deviation about the mean was observed for fields with the same land-cover type, compared with just regressing soil moisture over a 1 day time step.

## PREDICTION OF SOIL MOISTURE

### *Prediction of soil moisture in Little Washita, OK*

There have been many attempts to predict accurately and compute soil moisture from measurements such as brightness temperature, dielectric properties of the soil, electric resistivity, and various meteorological parameters, such as air temperature and skin surface temperature. In this section, we attempt to utilize *in situ* surface temperature collected during both studies and create a simple linear regression model for each field to predict soil moisture.

The model utilized (for SGP 99) only the *in situ* surface temperature and soil moisture collected between 8 July and 16 July 1999 (both days inclusive) to create the linear regression models. The *in situ* surface temperature measured between 17 July and 20 July 1999 (both days inclusive) was then used as input into this model to predict soil moisture for these four (17–20 July) days. Note: owing to the lack of adequate number of data points (only 5 days), the prediction capability of the regression relation between surface temperature and soil moisture was not carried out for the Little River 2000 watershed.

*In situ prediction of soil moisture.* Table V shows the results for the prediction of soil moisture at both depths (0–2·5 and 2·5–5·0 cm) between 17 July and 20 July 1999 (both days inclusive) for all of the fields sampled during SGP99 with the exception of LW05 and LW24–LW27. These fields were not a part of the analysis because they were not sampled for surface temperature (LW05) and soil moisture (LW24–LW27) in the field for the above-mentioned days. Certain other fields do not have values on selected days, as surface temperature was not measured on those days.

The linear regression results show that rangeland fields have a better prediction capability (mean difference between observations and prediction 0·05) than the wheat fields (mean difference between observations and prediction 0·10). However, if field LW08 (wheat field) is excluded from these comparisons, both the rangeland and wheat cover have similar statistics (mean difference between observations and prediction

Table V. Linear regression analysis of the Little Washita fields. The O column represents the observed volumetric soil moisture in the field during 10–16 July 1999. The P column represents the predicted volumetric soil moisture for 17–20 July 1999 from the linear regression equation which used the surface temperature and soil moisture values from 10–16 July 1999 to estimate. The Diff. column represents the difference between the observed and predicted volumetric soil moisture values

| Field | depth | Soil moisture | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 17 July 1999 | | | 18 July 1999 | | | 19 July 1999 | | | 20 July 1999 | | |
| | | O | P | Diff. | O | P | Diff. | O | P | Diff. | O | P | Diff. |
| 02 | 2·5 | 0·07 | 0·20 | 0·13 | | | | | | | 0·07 | 0·12 | 0·05 |
| 02 | 5·0 | 0·08 | 0·19 | 0·11 | | | | | | | 0·08 | 0·13 | 0·05 |
| 03 | 2·5 | 0·11 | 0·17 | 0·06 | 0·07 | 0·14 | 0·07 | 0·09 | 0·05 | 0·04 | 0·04 | 0·15 | 0·11 |
| 03 | 5·0 | 0·11 | 0·17 | 0·06 | 0·07 | 0·14 | 0·07 | 0·10 | 0·06 | 0·04 | 0·05 | 0·15 | 0·10 |
| 04 | 2·5 | 0·12 | 0·23 | 0·11 | 0·09 | 0·20 | 0·11 | 0·05 | 0·03 | 0·02 | | | |
| 04 | 5·0 | 0·12 | 0·21 | 0·09 | 0·09 | 0·18 | 0·09 | 0·06 | 0·04 | 0·02 | | | |
| 06 | 2·5 | 0·07 | 0·04 | 0·03 | 0·05 | 0·04 | 0·01 | | | | 0·06 | 0·04 | 0·02 |
| 06 | 5·0 | 0·07 | 0·04 | 0·03 | 0·05 | 0·00 | 0·05 | | | | 0·06 | 0·04 | 0·02 |
| 07 | 2·5 | 0·16 | 0·13 | 0·03 | | | | 0·17 | 0·05 | 0·12 | | | |
| 07 | 5·0 | 0·16 | 0·13 | 0·03 | | | | 0·15 | 0·06 | 0·09 | | | |
| 08 | 2·5 | | | | 0·15 | 0·45 | 0·30 | 0·05 | 0·45 | 0·40 | | | |
| 08 | 5·0 | | | | 0·17 | 0·45 | 0·28 | 0·11 | 0·45 | 0·34 | | | |
| 09 | 2·5 | 0·24 | 0·28 | 0·04 | 0·22 | 0·23 | 0·01 | | | | 0·08 | 0·27 | 0·19 |
| 09 | 5·0 | 0·21 | 0·26 | 0·05 | 0·21 | 0·22 | 0·01 | | | | 0·10 | 0·25 | 0·15 |
| 12 | 2·5 | 0·10 | 0·10 | 0·00 | 0·06 | 0·09 | 0·03 | 0·06 | 0·00 | 0·06 | 0·05 | 0·04 | 0·01 |
| 12 | 5·0 | 0·10 | 0·10 | 0·00 | 0·07 | 0·08 | 0·01 | 0·06 | 0·04 | 0·02 | 0·06 | 0·04 | 0·02 |
| 13 | 2·5 | 0·06 | 0·10 | 0·04 | 0·06 | 0·11 | 0·05 | 0·05 | 0·08 | 0·03 | 0·05 | 0·00 | 0·05 |
| 13 | 5·0 | 0·03 | 0·10 | 0·07 | 0·03 | 0·10 | 0·07 | 0·05 | 0·08 | 0·03 | 0·05 | 0·01 | 0·04 |
| 14 | 2·5 | 0·03 | 0·09 | 0·06 | 0·03 | 0·05 | 0·02 | | | | 0·02 | 0·08 | 0·06 |
| 14 | 5·0 | 0·04 | 0·09 | 0·05 | 0·03 | 0·05 | 0·02 | | | | 0·02 | 0·08 | 0·06 |
| 21 | 2·5 | | | | 0·10 | 0·12 | 0·02 | 0·07 | 0·05 | 0·02 | | | |
| 21 | 5·0 | | | | 0·12 | 0·16 | 0·04 | 0·09 | 0·10 | 0·01 | | | |
| 22 | 2·5 | 0·10 | 0·17 | 0·07 | 0·15 | 0·10 | 0·05 | 0·08 | 0·09 | 0·01 | 0·09 | 0·19 | 0·10 |
| 22 | 5·0 | 0·13 | 0·19 | 0·06 | 0·17 | 0·12 | 0·05 | 0·08 | 0·11 | 0·03 | 0·10 | 0·21 | 0·11 |
| 23 | 2·5 | 0·08 | 0·16 | 0·08 | 0·06 | 0·14 | 0·08 | 0·08 | 0·08 | 0·00 | 0·07 | 0·17 | 0·10 |
| 23 | 5·0 | 0·10 | 0·17 | 0·07 | 0·09 | 0·15 | 0·06 | 0·10 | 0·10 | 0·00 | 0·09 | 0·18 | 0·09 |

0·05). We did not observe a significant overestimation or underestimation by the linear regression model for rangeland fields, but we did see a significant overestimation for wheat fields. We assumed that the watershed was a sandy loam with saturation soil moisture of 0·45 (maximum) and a residual soil moisture of 0·04 (minimum). Any predictions that were greater than 0·45 were set to a value of 0·45 and any predictions that were lower than 0·04 were given the value of 0·04. On average, the difference between the observed soil moisture at 0–2·5 cm and the predicted soil moisture at the same depth is 0·07, with a range of difference values of 0·00 to 0·40. Field LW08 produced results that were not typical compared with all of the other fields sampled. The reason may be due to the effect of this particular vegetation, for LW08 was the only wheat field during the study (other wheat fields (LW21, 22, 23) were actually classified as weeds).

The results of the examination of the 0–2·5 and 0–5 cm soil moisture for observed and predicted values for all fields and wheat and range fields (for both depths) are shown in Figure 9. It can be seen that there is a very reasonable agreement between the soil moisture that is observed and the predicted value. The low value of the correlation coefficient $R^2$ is misleading, as this is influenced by a few bad predictions; in general, the agreements are within 0·05–0·1 of each other.

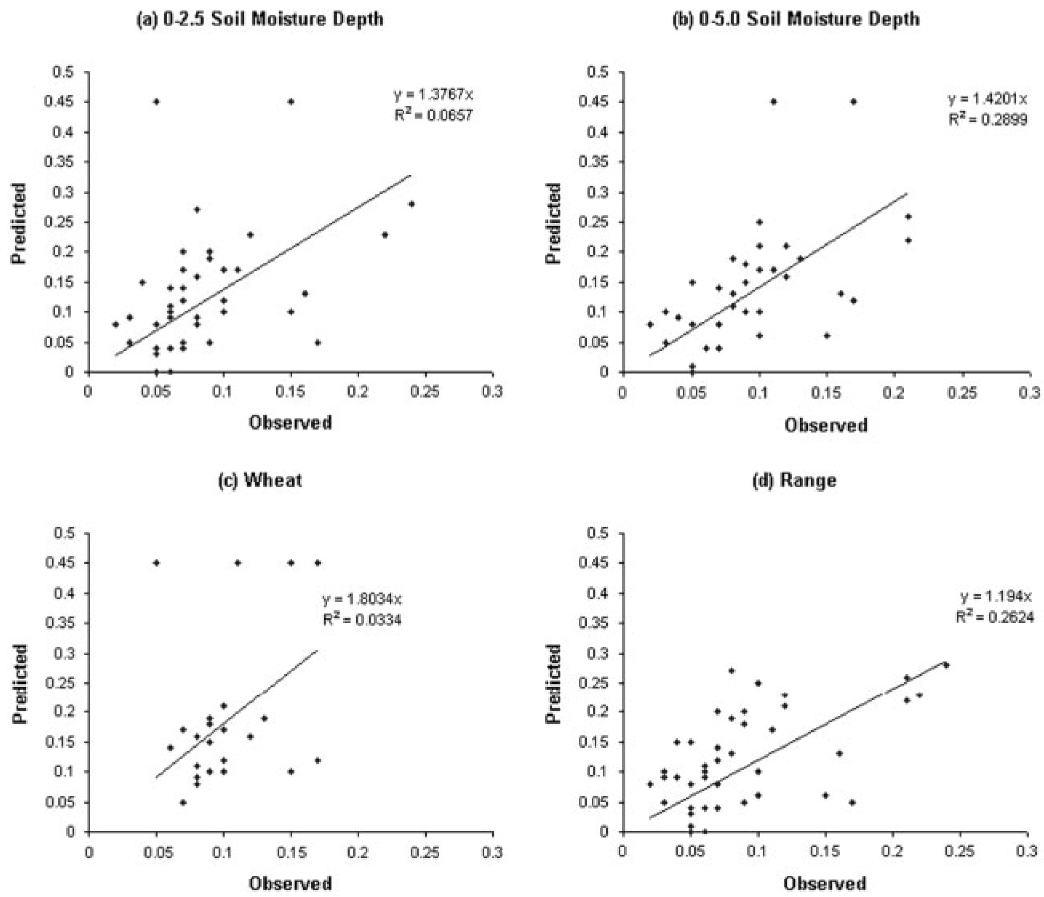


Figure 9. Comparison of the observed and predicted soil moisture at (a) 0–2·5 cm depth for all fields, (b) 0–5·0 cm depth for all fields, (c) wheat fields at both 0–2·5 and 0–5·0 cm depths, and (d) range fields for 0–2·5 and 0–5·0 cm depths

 

## CONCLUSIONS AND DISCUSSION

This study established relationships between soil moisture and surface temperature measurements that were made simultaneously in time and collocated in space. The use of surface temperature as a proxy for insufficient measurements of soil moisture and/or disaggregation of coarse-resolution soil moisture measurements using surface temperature was studied.

In the first part of the study, we examined the evolution of temperature with soil moisture after a precipitation event. The time history of temperature and moisture follow an inverse relationship, i.e. following a drydown, soil moisture decreases and the temperature increases.

We find a linear relationship between the measurements of surface temperature and the 0–2·5 and 2·5–5·0 cm volumetric soil moisture. Use of this linear relationship for prediction of soil moisture using the surface temperature measurements in the case of Little Washita (SGP99) yields good results.

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